Multiple production of charged particles in high-energy e^+e^- collisions

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A simple model is proposed in which the charged-particle multiplicity in e^+e^- annihilation at high energies is related to the emission of $B\bar{B}$ pairs with a small relative momentum between the B and the $\bar{B}$.

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Recent experiments have shown that the average charged-particle multiplicity in e^+e^- collisions increases more rapidly with increasing energy than would follow from the customary logarithmic dependence. Furthermore, it is important to note that this change in behavior occurs at energies $\sqrt{s} \sim 5$–6 GeV, at which the yield of baryon–antibaryon pairs also becomes significantly enhanced.[1,2] Beyond this point (Fig. 1), the charged-particle multiplicity and the $B\bar{B}$ yield increase in approximately the same way (over the range of the energy $\sqrt{s}$ which has been studied). In this letter we wish to point out a possible fundamental relationship between these phenomena.

We believe that the multiple production in e^+e^- collisions occurs in two steps: First,

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a "$B\bar{B}$" pair is produced; then, as a result of the strong interaction between the members of this pair, they either transform into real B and $\bar{B}$ or annihilate into mesons. Let us assume further that "$B\bar{B}$" pairs with small relative momenta are produced preferentially. This could happen for several reasons. First, it is easy to see that incorporating the final-state interaction substantially increases the probability for the production of $B\bar{B}$ pairs with small relative momenta. To show this, we denote by W the probability for the production of the pair B and $\bar{B}$, and we denote by W_0 the corresponding probability for "$B\bar{B}$"; then we can write

$$W = W_0 | \Psi_v (0) |^2, \tag{1}$$

where $|\Psi_v(0)|^2$ is the enhancement coefficient introduced by Fermi.[3] In the case of an attractive potential, which the $B\bar{B}$ potential is at low energies, this coefficient may be quite large. For example, if there is a level with a binding energy ϵ in a square potential of depth U, then we have the following expression for a given kinetic energy E of the $B\bar{B}$ pair in the c.m. frame:

$$| \Psi_v (0)|^2 \cong \frac{U + E}{\epsilon + E} . \tag{2}$$

We can thus see that if the level is close to the threshold, i.e., if $\epsilon \ll U$, then the enhancement coefficient may be large at small values of E. Calculations with realistic potentials show that near the $B\bar{B}$ threshold we can expect to find a state spectrum of a quasinuclear nature.[4] Another possibility for the preferential production of $B\bar{B}$ pairs with small relative momenta is that these pairs are produced in the decay of heavy resonances which are themselves produced in the initial stage of the interaction of the colliding particles. Finally, if "colored" "B" and "$\bar{B}$" are produced initially, then it would be natural to think—without appealing to the hypothesis of "soft bleaching"—that they are produced in pairs with a small relative momentum.

Let us express the charged-particle multiplicity in terms of the parameters of the $P\bar{P}$ interaction at low energies. We assume that the average number of "$B\bar{B}$" pairs produced in a collision is $\bar{N}$. We denote by α the probability that the "$B\bar{B}$" pair will convert into observable B and $\bar{B}$ after the interaction. We assume that the probability for the production of the $B\bar{B}$ pair and also α are independent of the type of baryon ($B \equiv p, n, \Lambda$). If so, the charged-particle multiplicity N_{ch} can be expressed in terms of $\bar{N}$ as follows:

$$N_{ch} = \left[\frac{2}{3} a + (1 - a) n_{ch} \right] \bar{N} , \tag{3}$$

where n_{ch} is the charged-particle multiplicity in $B\bar{B}$ annihilation at low energies. In (3) we have ignored the annihilationless production of π mesons, which would make a contribution $\lesssim 5\%$ to the $P\bar{P}$ annihilation near the threshold. For estimates we assume $\alpha(B\bar{B}) = \alpha(P\bar{P}) = (\sigma_{el}/\sigma_{tot})(p\bar{p})$. Over a rather broad energy range near the threshold we have $\sigma_{el}/\sigma_{tot} = 1/3$. For $P\bar{P}$ annihilation at rest, we have $n_{ch} = 3.05$. From these values we find $N_{ch} = 2.26\bar{N}$. To evaluate $\bar{N}$ we can use the expression[5] which is valid at large values of $\bar{N}$ in the ultrarelativistic approximation:

$$\bar{N} = N_0 \left(\frac{s}{s_0} \right)^{\gamma}, \tag{4}$$

where $\sqrt{s}$ is the energy in the c.m. frame of the colliding particles. The exponent here is $\gamma = \frac{1}{3}$ if the probability for the process is proportional to the invariant phase volume; alternatively, it is $\gamma = \frac{3}{8}$ if the emission of the "$B\bar{B}$" pairs is preceded by the attainment of a statistical equilibrium in the interaction volume.[6]

The value of N_0 can be determined from data on the production of $P\bar{P}$ pairs in the e^+e^- interaction. For a normalization we use the yield of $P\bar{P}$ pairs per event in the background in the region of the Υ meson ($\sqrt{s} = 9.45$ GeV): $\bar{P}P$/event $= 0.22 \pm 0.04$ (Ref. 7). The following relation must thus hold: $(1/3)N_0\alpha = 0.22$. Hence, $N_0 \cong 2$. This seems a reasonable value for N_0, for the following reasons. The emission of a "$B\bar{B}$" pair with a small relative momentum should be manifested as a hadron jet; in other words, the number of these "$B\bar{B}$" pairs and the number of jets are the same in this model. In the region of the Υ meson, we know that two-jet production of hadrons is predominant in the background events.

Figure 1 compares the calculated values of N_{ch} with the available data on the charged-particle multiplicity in the e^+e^- interaction. The theoretical curves with $\gamma = \frac{1}{3}$ and $\gamma = \frac{3}{8}$

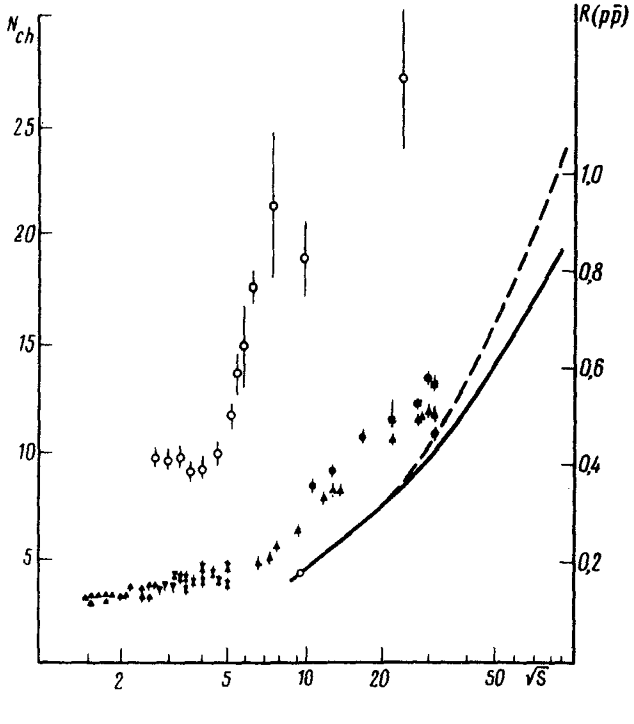

FIG. 1. Charged-particle multiplicity and the yield of $P\bar{P}$ pairs (shown by the circles) in e^+e^- annihilation. Solid curve–Theoretical $N_{ch}(s)$ dependence with $\gamma = \frac{1}{3}$; dashed curve–the same, with $\gamma = \frac{3}{8}$.

describe the $N_{ch}(s)$ dependence equally well over the energy range which has been studied. The calculated values of N_{ch} are slightly smaller than those observed experimentally (by something on the order of 20%). A possible reason for this discrepancy is our use as n_{ch} of the value corresponding to $\overline{P}P$ annihilation at rest. With increasing energy, the charged-particle multiplicity in $\overline{P}P$ annihilation increases in accordance with $n_{ch} = a + b\sqrt{s}$, so that for any nonzero relative momentum we should have $n_{ch} \gtrsim 3.05$, which would give us a corresponding increase in N_{ch}.

With regard to the applicability of this model to hadron-hadron collisions, we should note the following in this case. In hadron-hadron collisions most of the energy is carried off by leading particles. For example, if we write the energy $\sqrt{s_x}$ per "fireball" in the form $\sqrt{s_x} = (1 - k)\sqrt{s}$, where $\sqrt{s}$ is the total energy in the c.m. frame, then the coefficient k is approximately $k \approx 0.75$. In the case of the $\overline{P}P$ interaction at the energy $\sqrt{s} = 540$ GeV, we would thus find $N_{ch} = 26$ to 32 for $\gamma = \frac{1}{3}$ to $\frac{3}{8}$, in extremely close agreement with experiment.[8] The description of the behavior $N_{ch}(s)$ in hadron-hadron collisions remains an open question in this model, since it cannot be resolved without a clear identification of the phenomenon of interest here against the background of multiperipheral processes.

This model has several experimental consequences: a) In e^+e^- collisions at high energies, a comparatively large number of $B\overline{B}$ pairs with small relative momenta between the B and $\overline{B}$ should be observed. The number of such pairs will increase in accordance with $\overline{N} = N_0(s/s_0)^\gamma$. b) The number of hadron jets should behave in the same way. c) The charged-particle multiplicity in a jet, N^0_{ch}, should be given approximately by $N^0_{ch} = 2/9 + 2/3\, n_{ch} = 2.26$. d) In each event, the ratio of the number of $B\overline{B}$ pairs to the number of jets should have an upper limit of order $\alpha(BB) \cong \frac{1}{3}$. e) The ratio of the antiproton yield to the π-meson yield should be of order $\overline{p}/\pi \cong \alpha/3(1-\alpha)n_{ch} \cong 1/18(\sim 6\%)$. f) The angular dimensions of a jet should fall off with increasing energy of the colliding particles, in accordance with $\overline{\theta} \approx \langle p_\perp \rangle / \langle p^\parallel \rangle = \langle p_\pi \rangle / \sqrt{s}\overline{N} \sim s^{\gamma - 1/2}$ (here $\langle p_\pi \rangle = \langle p_\perp \rangle$; i.e., the average momentum of the π meson in $\overline{P}P$ annihilation near the threshold is equal to the average value $\langle p_\perp \rangle$, with respect to the jet axis, in this model). g) It would be interesting to see a study of the invariant-mass spectrum of the $B\overline{B}$ systems and also of hadron jets. Such a study could, in principle, yield information about heavy entities whose decay product might be experimentally observable $B\overline{B}$ pairs. h) A significant fraction of the events should have no π mesons. The probability for such an event varies in proportion to $\alpha^{\overline{N}}$. At energies in the Υ region ($\sqrt{s} \sim 10$ GeV) this probability is $\sim \alpha^2 = \frac{1}{9}$ ($\sim 10\%$). In the case of the $\overline{P}P$ interaction at energies in the colliding-beam region ($\sqrt{s} = 540$ GeV) the relative probability for such events should be on the order of 10^{-5}. We may expect events of this nature to be responsible, in particular, for the observation of "centaur" events, since in this case there are no γ rays from π^0 decay, and this is a distinguishing feature of a centaur event. In this model, the centaurs are events which correspond to the production of only baryon-antibaryon pairs.

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